Determination of Biological Conditions Using Impedance Measurements

This application claims priority from U.S. Patent Application Serial No. 60/417,561, filed on October 11, 2002, the contents of which are incorporated herein by reference.

Field of the invention

This invention is in the field of diagnostics of biological conditions. In one aspect, the invention involves *in vivo* evaluation of the level of a substance in the blood of a subject, particularly blood glucose levels. In another aspect, the invention involves diagnosing a diseased condition of the skin of a subject, particularly the presence of a skin cancer, e.g. basal cell carcinoma or malignant melanoma, a squamous cell carcinoma or precursors thereof. In both instances, the determination is based on skin impedance measurements.

Background of the invention

Non-invasive methods of making biological determinations are generally desirable over invasive techniques that involve the taking of samples. Non-invasive techniques can be more convenient, e.g., less painful, involve less risk of infection, etc. Non-invasive techniques for evaluating blood glucose levels have been described in the patent literature:

Application No.	Publication No.	Publication Date	Name
	US 5,036,861	August 6, 1991	Sembrowich *et al.*
	US 5,115,133	May 19, 1992	Knudson
	US 5,146,091	September 8, 1992	Knudson
	US 5,197, 951	January 19, 1993	Knudson
	US 5,222,496	June 29, 1993	Clarke *et al.*
PCT/US 94/08816	WO 95/04496	February 16, 1995	Solid State Farms, Inc.
	US 5,433,197	July 18, 1995	Stark
PCT/US 97/13267	WO 98/04190	February 5, 1998	Dermal Therapy (Barbados) Inc.
PCT/US 98/02037	WO 99/39627	August 12, 1999	Dermal Therapy (Barbados) Inc.
PCT/IB 00/01464	WO 01/26538	October 13, 2000	S► sstrunk, *et al.*

Summary of the invention

A summary of the invention in its various aspects is provided in the attached claims, bearing in mind that those skilled in the art will understand that a variety of possible combinations and subcombinations of the various elements described in the claims and throughout this specification exist, and all of these combinations and subcombinations should be considered to be within the inventors' contemplation though not explicitly enumerated here. This is also true of the variety of aspects of the processes and the combinations and subcombinations of elements thereof.

Description of drawings

The invention is described in greater detail below, with reference to the attached figures, in which:

Figure 1(a) shows a spiked electrode of the present invention;

Figure 1 (b) shows details of the spiked array given as electron micrograph;

Figure 2 shows representative Bode plots of impedance (left hand axis, kOhms) and phase (right hand axis; degrees) as a function of frequency number (31 logarithmically distributed frequencies from 1kHz to 1 MHz) for subject B. The results shown in Figure 2(a) were obtained using a conventional probe and those shown in Figure 2(b) were obtained using a spiked electrode. In Figure 2(a), the lower set of curves shows the magnitude of the impedance (at various depths) and the corresponding phase is shown by the upper set of curves. In Figure 2(b), the phase plots display a local maximum around frequency number 21;

Figure 3 shows the blood glucose level as determined directly over the course of the tests for each subject. Subject A (◆), subject B (●);

Figure 4(a) shows a scatter plot of PCA (principle component analysis) for each subject (t1 vs. t2) obtained with the spiked electrode. Figure 4(b) is a corresponding plot for each subject obtained with the conventional probe. In both plots, subject A is to the right and subject B is to the left of the figure;

Figure 5(a) shows a scatter plot of measured blood glucose and index with outliers of subject A obtained with the spiked electrode. Figure 5(b) shows the same plot without outliers, readings number 7, 8, and 13;

Figure 6(a) shows a scatter plot of subject B's blood glucose vs. magnitude of impedance at 1 MHz and depth setting number 5 measured with the spiked electrode with (left) outlier reading number 10. Figure 6(b) is the same plot without the outlier;

Figure 7 shows a scatter plot of subject B's magnitude at 1 kHz and depth setting number 5 vs. blood glucose;

Figure 8 shows representative Bode plots of impedance (left hand axis; kOhm) and phase angle (right hand axis; degrees) as a function of frequency (kHz), plotted logarithmically, obtained at five depth settings using a spiked electrode. In Figure 8(a), the results were obtained for a normal skin site of a subject. In Figure 8(b), the results were obtained from the same subject but a basal cell carcinoma located near the normal site of Figure 8(a). In Figure 8(c), the results were obtained from a normal skin site of another subject. In Figure 8(d), the results were obtained from this other subject but a malignant melanoma located near the normal site of Figure 8(c). Each ensemble of curves represents five measured depths.

Figure 9 shows a correlation between blood glucose and values obtained from impedance measurements taken using a multi-step inundation method and conventional electrode.

Description of preferred embodiments

An apparatus for use according to the present invention can generally be regarded as a combination of the device described in international patent application No. PCT/SE 91/00703, published under WO 92/06634 on April 30, 1992 and the "spiked" electrode described in international patent application No. PCT/IB 01/00059, published under WO 01/52731 on July 26, 2001 or in an article entitled "Micromachined Electrodes for Biopotential Measurements" published in the Journal of Microelectromechanical Systems **10(1)**, pp 10-16, on March 2001 by Griss *et al.* The electrode used in the tests described below, however, is a variation of that described by Griss *et al.*, and is shown if Figures 1(a) and 1(b). The probe includes of a number of electrodes, at least three according to No. PCT/SE 91/00703, and in the present invention each electrode of the probe has a spiked surface, which permits measurements to be made at a variety of skin depths. The probe is illustrated in Figure 1(b), the probe being viewed looking down onto its spikes (a bottom plan view). The probe includes three rectangular areas or bars each bar containing an array of 35 (7 x5) spikes. Each bar is 1 mm wide and 5 mm long. The

distance between the closest bars is 0.2 mm, and the wider between the second and third bars is 1.8 mm. The active part of the probe is thus about 5 x 5 mm. Each spike has a length of approximately 150 micrometer, as measured from its base, and a thickness of approximately 25 micrometer. The spikes are sharpened cylinders, i.e. are needle-like, and spaced approximately 200 micrometers from each other, center to center. The spikes were of silicon and covered with gold approximately 2 micrometer thick. Any material comprising a conductive surface with similar dimensions would work, but should be selected to be biocompatible.

The apparatus, without the spiked probe known as the SciBase II depth selective spectrometer, may be obtained from SciBase AB of Huddinge, Sweden. The pin assignment for the probe connector was as follows:

1. <START> button
2. sense (first electrode illustrated Figure 1(b); use coaxial (conventional probe) screen 3.
3. gnd (for sense)
4. near exciter (second (middle) electrode illustrated in Figure 1(b) ; use coaxial (conventional probe) screen 5.
5. gnd (for near injection).
6. gnd.
7. far exciter (third (right-most) electrode illustrated in Figure 1(b) ; use coaxial (conventional probe) screen 8.
8. gnd (for far injection).
9. chassis.
10. reserved.
11. reserved.
12. gnd.
13. gnd.
14.
15. charger.

Blood glucose levels

Tests were conducted using the foregoing apparatus to determine the feasibility of using such apparatus in determining blood glucose levels of human beings. Trials were conducted on two individuals, subjects A and B. Subject A suffers from atopic dermatitis, making the subject a relatively poor candidate for a non-invasive determination involving a skin measurement.

Tests were thus carried out (i) to assess the correlation between skin impedance measured using the spiked electrodes and the blood glucose, and (ii) to compare the glucose correlation of impedance measured with a conventional probe and the spiked electrodes.

Two sites, one on each arm, were marked. One site was used for the spiked probe and the other for the conventional probe. Blood glucose levels were measured directly using the Glucometer Elite (available from Elite Glucometer, Miles Canada, Diagnostics Division, Division of Bayer). The sites were soaked for 60 seconds prior to each impedance measurement using 0.9% saline solution and stopwatch. Impedance was measured using the SciBase II depth selective spectrometer at 31 logarithmically distributed frequencies from 1 kHz to 1 MHz at five depth settings, as described in PCT/SE /00703.

The correlation between impedance and blood glucose was evaluated in three steps with increasing complexity of the regression models. The first step is linear regression between raw impedance and blood glucose for each frequency, depth setting and impedance presentation (magnitude, phase, real part, and imaginary part). The second step is linear regression between indices and blood glucose. The indices are described in detail below. The last step is partial least squares regression (PLS) models of full impedance spectra and glucose levels.

As indicated in Figure 2, the magnitude of the impedance measured with the regular probe (Figure 2(a)) was found to be much higher along with the phase, and the characteristic frequency was lower. Hence, impedance measured with the conventional probe was significantly different from the spiked electrodes.

The tests were carried out over about 5 hours. The electrodes with spikes used to measure impedance of subject B broke down after approximately 10-11 readings. The glucose levels for subject A and B, as measured directly, are shown in Figure 3. The glucose levels of subject A were generally higher than for subject B, and the impedance of the two volunteers was also found to be different, as indicated in Figure 4. This indicates that it might not be possible to use one calibration model for these subjects.

The four indices (MIX, PIX, RIX, and IMIX) were originally made to normalise impedance spectra of the spectrometer. It was found that the four indices described a substantial part of the variations in the impedance spectra and were useful in skin irritation assessments, but not necessarily in glucose quantifications. Therefore, new indices, ix, were made using the frequencies, f, depth settings, d, for all impedance presentations, X, according to (1).

$$\mathrm{ix}(i,j,k,l,m,n) = \frac{X_i(f_j, d_k)}{X_l(f_m, d_n)} \qquad (1)$$

$$i, k \in 1 \ldots 4$$
$$X_1 = |Z|, X_2 = \theta, X_3 = \mathrm{Re}(Z), X_4 = \mathrm{Im}(Z)$$
$$f_j, f_m \in 1\mathrm{kHz} \ldots 1\mathrm{Mhz}$$
$$d_k, d_n \in 1 \ldots 5$$

Three impedance readings were abnormal and excluded from the data analysis. Correlation coefficient (R2) of linear regression between an impedance index of the results obtained with the spiked electrode and subject A's blood glucose was 70% (n=11). This is shown in Figure 5. The new index used in this analysis is based on only two frequencies, each frequency measured at different depth settings, and is defined as:

$$\mathrm{ix} = \frac{\mathrm{Re}(Z_{20\,\mathrm{kHz,\,depth\,\#5}})}{|Z_{500\,\mathrm{kHz,\,depth\,\#3}}|}$$

In the case of the conventional probe, no significant correlation was found between impedance measured and blood glucose for subject A.

In the case of subject B and the results obtained with the spiked electrode, there was one reading with abnormal impedance. The measurement was made just before the spiked probe broke down and it is believed that the impedance of the actual reading was abnormal because the spiked probe was beginning to malfunction when the last measurement was made. Linear regression between the magnitude of the raw impedance at high frequencies and deep depths and blood glucose showed good correlation, $R^2 = 80\%$ (n=9). See Figure 6.

No significant impedance/glucose correlation was found using the conventional concentric probe if all the measurements were included. However, three readings, number 5, 10, and 11, do not show the same impedance/glucose pattern as the others (Figure 7). If these 3 readings are excluded, the correlation coefficient becomes approximately 95%. If these excluded readings are not considered outliers (there is nothing abnormal about their impedance or glucose

levels), the correlation between impedance measured with the regular probe and blood glucose would not be significant. However, suitable inundation and data exclusion criteria that might exclude these flawed measurements thus permitting accurate glucose predictions using the conventional probe at least under certain conditions.

The results described herein, summarized in Table 1, establish the improved correlation between measured skin impedance and blood glucose levels obtainable using the spiked electrode described above. It is the experience of the inventors, that a higher correlation can be achieved using the conventional probe with optimization of inundation time of the sample site.

Table 1: Summary of the correlation coefficient (R2) between blood glucose and skin impedance measured with the regular probe and the spikes.

Subject	Conventional Probe	Spiked Electrode
A	Not significant	~70%
B	Not significant	~80%

It is evident that there was a strong correlation between skin impedance and blood glucose in this experiment. The correlation of the two subjects was found more reliable for the spiked electrodes than the conventional probe.

The spiked electrodes can improve the glucose correlation by mitigating factors interfering with the impedance tests and reducing the stringency of skin inundation in preparing the site for impedance measurement. Thus the spiked electrodes are likely to permit glucose determination more reliably in a wider variety of situations than such determination with a conventional probe.

The following inundation procedures can be used to improve results obtained with the conventional probe. Gauze inundation pads are kept in a closed beaker of 0.9% saline or packaged in a saturated state. The skin is inundated by holding the gauze pad in place at the test site for 40 seconds then wiping away any excess solution before the impedance test., with inundation again 10 additional seconds, wiping away any excess solution before the second impedance test and impedance test again. This procedure is repeated until a total of 70 seconds of inundation has been reached.

Data are included if at 1 Mhz at depth 1 the kOhms value is within the range 1.25 –1.45. Other frequencies can be used. If more than one impedance test was within this range, the kOhm value closest to 1.3 is selected. If the kOhm value is in range and IMIX at depth one value is between 10.2 and 11.5 then this IMIX value is accepted. Results obtained over several days are shown in Figure 9.

The conditions under which reliable results are obtained using the probe having spiked electrodes are thus more relaxed than with the conventional probe. There is thus less likely to be a need for subjects to use a mild soap, for example, when using the spiked electrode. It may be possible to obtain reliable results with tanned or diseased skin (e.g., atopic dermatis) with the spiked probe where such was not possible with the conventional probe. It is also likely that use of the same site from measurement to measurement is less important when using the spiked probe than when using the conventional probe.

Cancer diagnosis

Impedance measurements were similarly taken from subjects suffering from basal cell carcinoma or malignant melanoma: at a first site of normal (unaffected skin); and at a second site, of diseased skin. Results obtained are shown in Figure 8. A further description of the approach, in which measurements were obtained using a conventional probe, is given in Emtestam I, Nicander I, Stenström M, Ollmar S. "Electrical impedance of nodular basal cell carcinoma: a pilot study", Dermatology 1998; **197**: 313-316, and Kapoor S. "Bioelectric impedance techniques for clinical detection of skin cancer", (MSc-thesis) University of Missouri-Rolla 2001, and Åberg P, Nicander I, Holmgren U, Geladi P, Ollmar S. Assessment of skin lesions and skin cancer using simple electrical impedance indices. Skin Res Technol 2003; 9: 257-261, and Beetner DG, Kapoor S, Manjunath S, Zhou X, Stoecker WV. Differentiation among basal cell carcinoma, benign lesions, and normal skin using electric impedance. IEEE Trans Biomed Eng 2003; 50: 1020-1025.

It is desirable to detect and remove skin cancers as early as possible. As such, precursors of skin cancer, such as, for example, actinic keratose (a precursor of squamous cell carcinoma) and dysplastic nevi (a precursor of malignant melanoma), as well as other lesions that may be

mixed up with various cancers unless surgery and histological evaluation of the catch is made, can be detected using impedance measurements of the present invention in the manner described herein.

The contents of all documents referred to herein are incorporated into this specification by reference as though such contents had been reproduced herein in their entirety.